

CONTRACTOR REPORT CR-9

PLANETARY AERONOMY III:
DETERMINATION OF ATMOSPHERIC PARAMETERS
BY THE USE OF ROCKET-BORNE
MASS SPECTROMETERS

By R. F. K. Herzog, F. F. Marmo, R. A. Minzner,
and G. O. Sauermann

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

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An experimental technique is described for obtaining various hydrodynamic and thermodynamic properties of the upper atmosphere. A typical data analysis has been performed on a hypothetical experiment. The analysis of the experimental data yielded information on the following: (1) The location and detection of the beginning of diffusive separation in the upper atmosphere; (2) a measure of the degree of diffusive separation in the transition region; (3) the location above which complete diffusive separation prevails; (4) an improved temperature-altitude profile from the beginning of diffusive separation up to extremely high altitudes; (5) determination of the temperature in the upper part of the mixed region of the atmosphere; (6) the possibility of detecting small perturbations of upper atmospheric temperature in local regions; and (7) a determination of the variation of mean molecular weight of the ambient air in the heterosphere.

AUTHOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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I. INTRODUCTION

The difficulty of the measurement of atmospheric parameters at high altitudes is increased by the fact that the composition changes considerably. These changes are caused (1) by gravitational separation and (2) by interaction with incoming radiation and secondary chemical processes. The change in composition can only be observed at high altitudes since at lower altitudes, turbulent mixing occurs with the result of an essentially homogeneous atmosphere. This statement is probably true for the atmospheres of the terrestrial planets; however, the height of the mictopause where the homosphere ends and the heterosphere starts, may be very different for the different planets. The measurement of all constituents of an atmosphere by mass spectroscopic means is a rather difficult task because the rapid change of pressures and composition on board a fast-moving vehicle requires a fast scan of the whole mass spectrum which necessarily reduces the sensitivity of the instrument and the accuracy of the measurement. One way out is to avoid the scanning completely and to measure a few specific components continuously. The present paper contains a discussion of such an experiment especially in regard to the information which can be derived from such measurements. For the purpose of this discussion, two rare gases--helium and argon--have been chosen since they are practically unaffected by incoming radiation and the ratio of the molecular weights is large which results in a

rather drastic gravitational separation. Krypton and xenon have been excluded because of the very low relative abundance which decreases even more at high altitudes. Helium, on the other hand, although only a minor constituent at low altitudes, has such a large scale height compared to the other components that it even becomes a major component at very high altitudes.

The following general discussions are applicable to any planetary atmosphere. However, the numerical examples are chosen to fit the Earth's atmosphere. This is well justified since the first application of the method described will probably take place here. In addition to this, much more information is presently available for the atmosphere of the Earth compared with those of other planets which permits a much more realistic discussion and evaluation of the problems involved.

In the Earth's atmosphere, several atmospheric parameters are fairly well known up to about 100 km. These parameters include ambient chemical composition, temperature, pressure, and other thermodynamic quantities directly related. In addition, it is generally agreed that the atmosphere is essentially mixed and that, in general, the various species are distributed according to a common number density-altitude profile. On the other hand, for higher altitudes the composition changes in a manner not sufficiently known today.

This is unfortunate since the knowledge of specific thermodynamic and hydrodynamic parameters is required in the study of almost any phase of

chemical aeronomy in the upper atmosphere. Accordingly, this higher region has been the target of several detailed recent studies.⁽¹⁾ It is not the purpose of the present paper to review or evaluate these studies. However, it should be noted that the present state of knowledge supports several different controversial points of view. This report describes an experiment designed specifically to determine some of the more important atmospheric parameters. In the proposed experiment, a mass spectrometer will obtain number density-altitude profiles for helium and argon. In particular, it will be shown that valuable information can be obtained regarding upper atmospheric temperatures and related thermodynamic properties, the micropause level, the transition region, the degree of mixing at various altitudes, and/or the extent to which hydrostatic equilibrium prevails. In addition, the helium number density determinations can be employed as a check on some of the latest theories⁽²⁾ concerning the role of helium in the Earth's upper atmosphere.

II. THEORETICAL ANALYSIS

A. GENERAL REMARKS

The performance of the experiment discussed should yield the following experimental data: (a) the helium number density-altitude profile to about 1000 km, (b) the argon number density-altitude profile up to about 250 km, and (c) an approximation to the total number density-altitude profile derived from the measurements of the total ion current.

To make optimum use of these data, it is important to accomplish a detailed theoretical analysis along with the required engineering and development program. A preliminary theoretical analysis has been performed and is given below. A more detailed analysis is given in a paper in preparation by G. O. Sauermann and R. A. Minzner. It will be shown that information can be obtained for the following phenomena: (1) the beginning of the micropause region; (2) the definition and altitude range of the transition region (between complete mixing and diffusive equilibrium; (3) separation effects in the region of complete diffusive equilibrium; (4) an approximate determination of the absolute temperature for the region of the atmosphere which is mixed; (5) an improved determination of the absolute temperature for the region of the atmosphere in diffusive equilibrium; and finally (6) the several thermodynamic properties associated with atmospheric temperature, composition, and number densities. It may be noted that Items 1, 2 and 3 can be associated with the dynamic properties of the upper atmosphere (winds) whereas Items 4,

5 and 6 can be classified as thermodynamic properties. It is convenient to discuss the appropriate theoretical analyses of each of these areas individually.

B. DYNAMIC PROPERTIES OF THE ATMOSPHERE

The Earth's atmosphere is well mixed below the so-called mictopause level which is assumed to be located at an altitude between 100 and 160 km. For instance, Meadows and Smith⁽³⁾ collecting composition information, deduce a mictopause level between 110 and 120 km. From the surface up to these altitudes, the relative helium concentration is essentially constant (5.24×10^{-6}) so that the helium partial pressure profile is directly proportional to the total pressure. Above this level, the partial pressure of helium decreases much slower than the total pressure. This gravitational separation effect is much more pronounced between A and He than between A and N_2 (which has been used so far for the determination of the mictopause level) because the mass ratio is 10 instead of 1.4. The partial pressure of helium at very high altitudes is mainly determined by the height of the mictopause and decreases only very slowly above it (about one order of magnitude per 1000 km). (See the Summary Report about "Helium in the Earth's Atmosphere" by Sauermann and Herzog.⁽⁴⁾) Measurement of the helium density-profiles for altitudes up to 250 km (e.g. from an Aerobee-Hi rocket) can yield information on the helium densities which can then be expected at much greater altitudes. For example, if one assumes 100 km as the height of the mictopause and neglects ionization and the helium escape phenomena,

then the helium content at higher altitudes can be evaluated on the basis of the 1959 ARDC Model Atmosphere. If this is done, it turns out that at about 1000 km, the number density of helium atoms is about equal to that of oxygen atoms, and above this level helium should become the main constituent of the atmosphere until one reaches the protosphere. The effort required to measure the helium partial pressure is, therefore, well justified. The first step toward this goal is the measurement of helium concentrations at medium altitudes which can be easily reached by rockets.

To obtain the theoretical density profile for helium, assumptions have to be made about the height of the mictopause (the separation level). Actually, the transition from mixing to diffusion is gradual and without sharp boundaries. Nevertheless, an idealized height for an abrupt change from mixing to diffusion can be defined in such a way that sufficiently below and above the transition region, the real and idealized (assuming a sharp separation level) density profiles are identical; this is shown in Figure 1 which illustrates the meaning of the "height of the mictopause," as employed in the present calculations.

In order to get a general picture, the helium density profile has been calculated for different heights of the mictopause and the results are shown in Figure 2 which illustrates that the helium density curves can shift considerably when the mictopause level changes only a few kilometers in height.

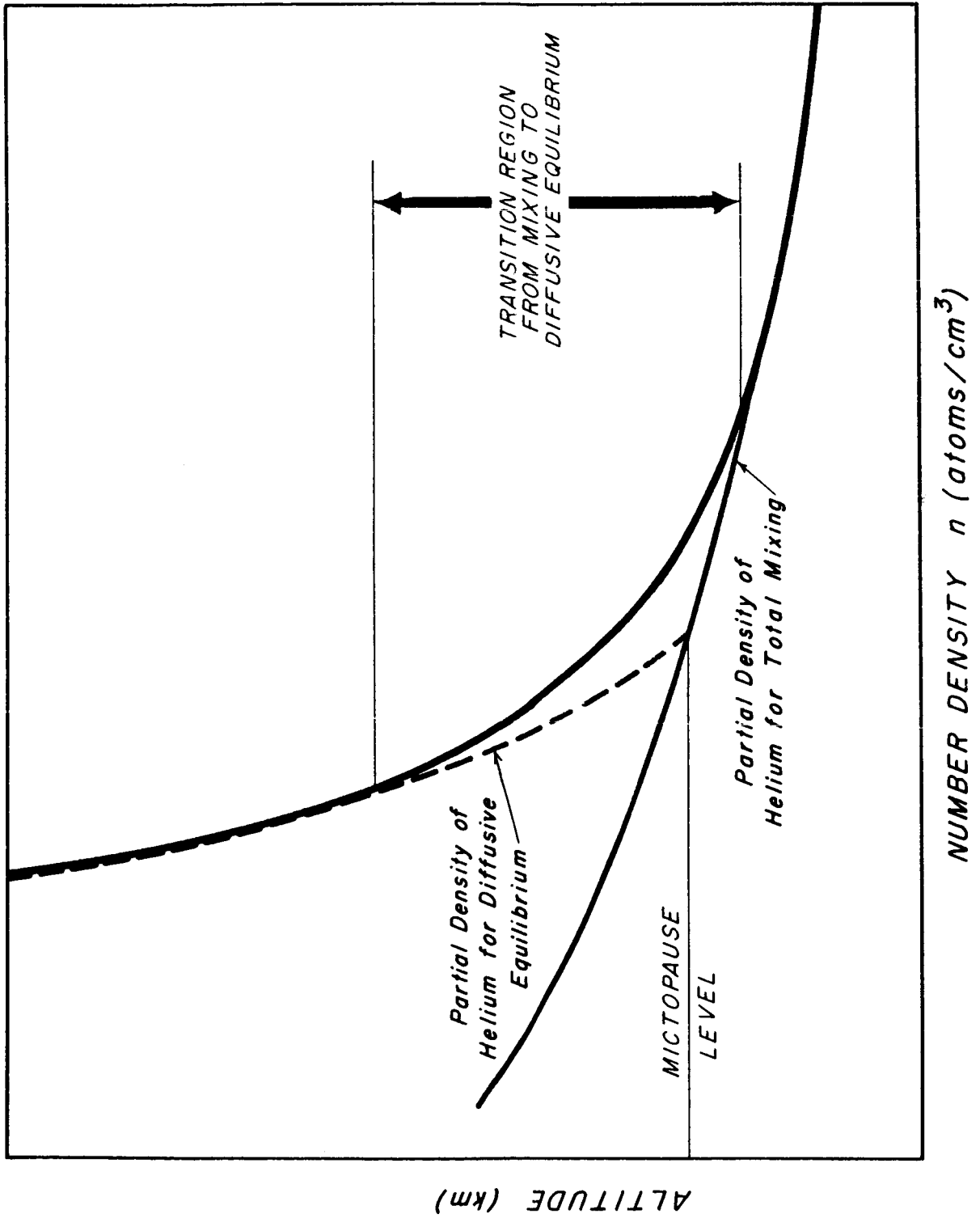


Figure 1. Definition of the Mictopause level.

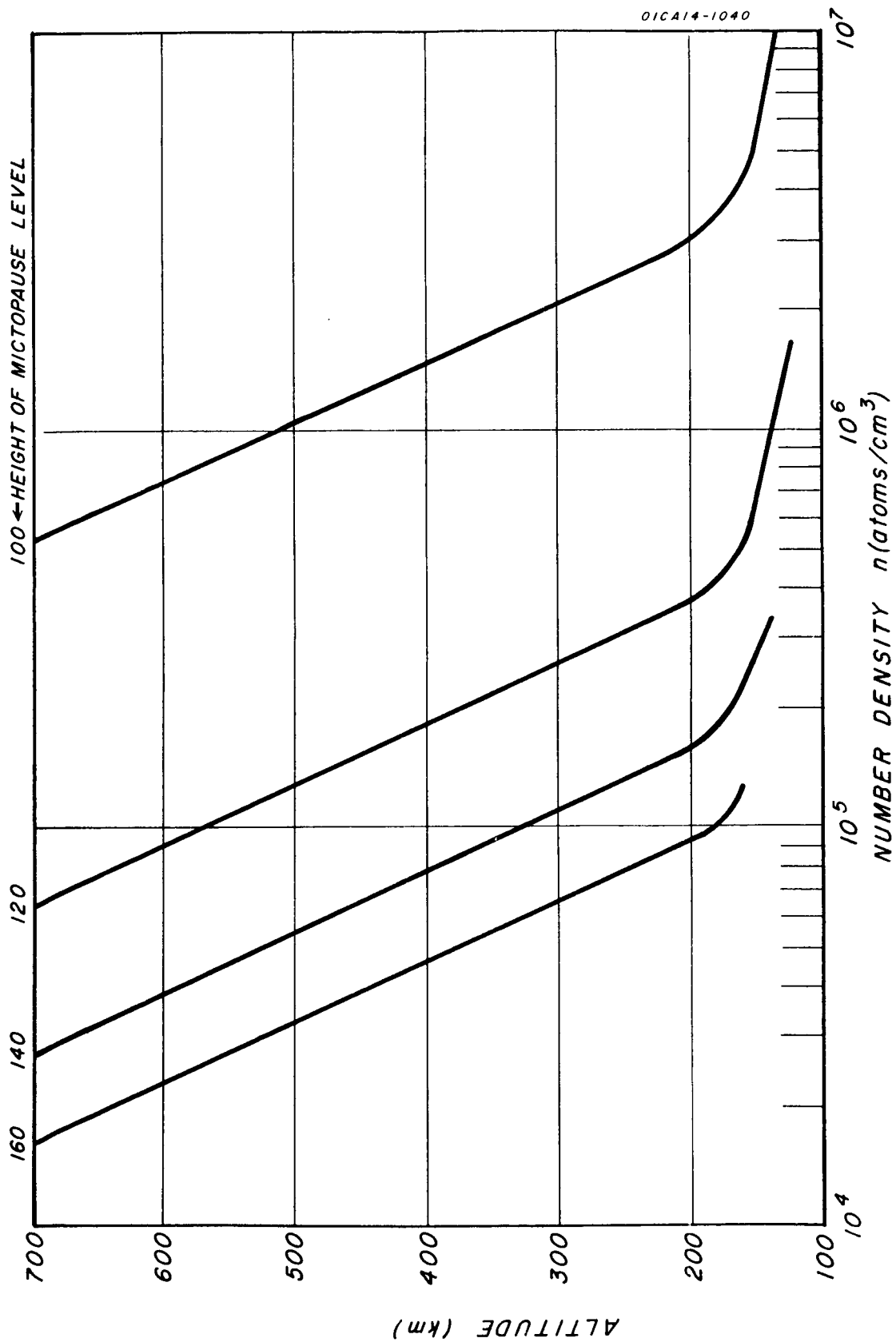


Figure 2. Helium density profile for various micropause levels.

In addition to the above, it has been shown that the time constant to establish diffusive equilibrium in the atmosphere is small. For example, P. Mange,⁽⁵⁾ based on studies of Maris,⁽⁶⁾ Epstein,⁽⁷⁾ and Sutton,⁽⁸⁾ has calculated the rapidity of diffusion in the atmosphere. From the results it can be deduced that the changes of the helium density profile at high altitudes can be correlated with the time variation of the mictopause level. Previous works have shown⁽⁴⁾ that the region above 800 km (but below about 2000 km) probably consists mainly of atomic oxygen and helium with their respective densities subject to great changes due to variations of the temperature, mictopause level, turbulence, etc. For example, the atomic-oxygen-altitude profile is very temperature sensitive (and not mictopause level sensitive), whereas the helium profile is mictopause level sensitive (but not very temperature sensitive). Accordingly, as a result, at very high altitudes (about 1600 km where helium outnumbers the oxygen), the density of the atmosphere is practically determined by phenomena which take place in the region between 100 and 150 km. In this regard, sodium measurements by E. Manring⁽⁹⁾ show that in the region between 80 and 120 km, strong and irregular winds with shifting velocities occur which suggests that the mictopause level is subject to considerable fluctuation. On the other hand, in the region between 400 and 1000 km, where the atmosphere consists mainly of oxygen atoms, large density changes occur due to heating effects. Figures 3 and 4 show the influence of the two effects mentioned above on the total density at great altitudes.

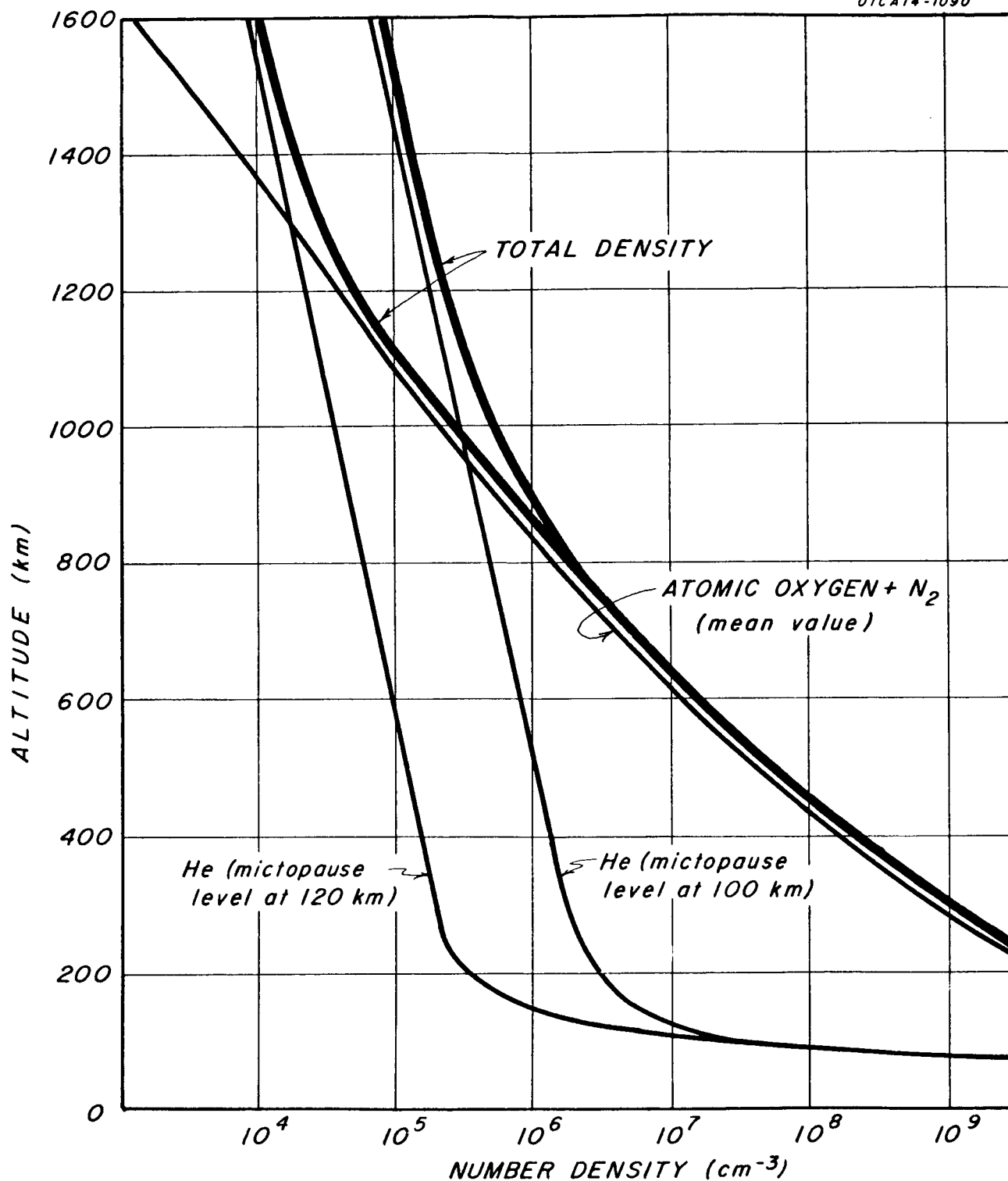


Figure 3. Estimated changes in total density due to changes in the height of the mictopause level (solar radiation is assumed to be constant).

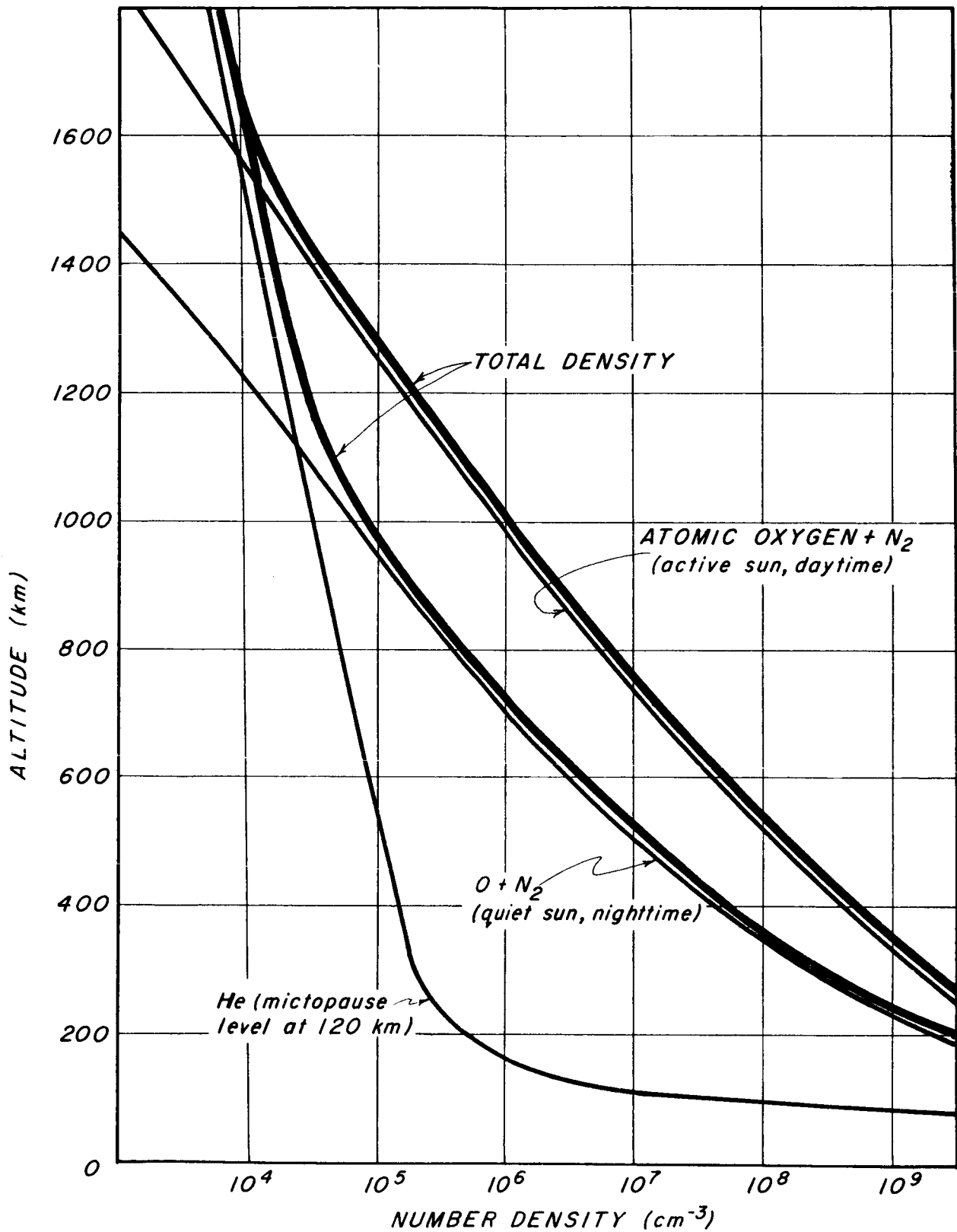


Figure 4. Estimated changes in total density due to changes in the solar radiation (height of the mictopause level is assumed to be constant).

The previous discussion has made clear the importance of locating the mictopause level. In practice, there probably exists a transition region rather than a sharp level. Diffusive separation should become apparent as the probe operates somewhat above 100 km. In this region, the separation ratio, r , can be determined by dividing the ratio argon-to-helium number density, as measured during the flight at a particular altitude, by the calibration ratio of argon-to-helium number density for normal, mixed, ground-level air. In other words, for $r = 1$, no diffusive separation is present; for $r = 0$, separation is complete. Several investigators⁽³⁾ have probed the argon-nitrogen ratio as a function of altitude. The current experiment is analogous to these except that in this case, the argon-to-helium number density ratio is employed.

The simple theory shows that the separation ratio behaves according to

$$r = \exp (- h/H_1) \quad (1)$$

where

$$H_1 = \frac{RT}{g(M^*-M)} ,$$

and

r = separation ratio

h = altitude interval above mictopause level

R = universal gas constant

T = average absolute temperature in interval h

g = average local value of gravity in interval h

M^* = mass number of heavy gas (i.e., argon)

M = mass number of light gas (i.e., helium)

The use of helium in place of nitrogen in the proposed experiments results in a ratio of molecular weights (therefore, scale heights) of 10 compared with less than 1.5 for the case of nitrogen. This factor will aid in a more accurate and sensitive determination of the height of the beginning of diffusive separation. It may be pointed out that although previous investigations have indicated the beginning of the diffusion level, none have successfully defined the region in which complete diffusive equilibrium prevails. Much of the difficulty was due to the fact that nitrogen was one of the gases probed. Accordingly, it becomes difficult--if not impossible--to correlate the peak heights against the ambient nitrogen content due to chemical reactivity, photo-ionization, instrumental dissociation, etc. These difficulties are minimized in the present probe.

C. THERMODYNAMIC PROPERTIES OF THE ATMOSPHERE

The knowledge of the temperature profile (i.e., the temperature distribution with height) is of great importance for the proper interpretation of many physical effects in any planetary atmosphere and for the understanding of the mechanism involved. In particular, even small changes

in the temperature profile can have considerable accumulative effects on the pressure and density distribution which, in turn, can affect the entire aeronomy of the upper atmosphere. Accordingly, the temperature, and the manner in which temperature varies with height, is one of the most important basic parameters associated with many other physical properties of an atmosphere. Any direct measurement of temperature in a significantly rarefied gas is currently impractical so that any attempt to determine the prevailing temperatures in the higher parts of any planetary atmosphere is a difficult problem in itself. On the other hand, any discussion of atmospheric properties has to be based on model atmospheres which cannot be generated without some realistic estimates of the temperature distribution with height. In the case of the Earth's atmosphere, model atmospheres can be set up by assuming certain temperature profiles which, in turn, have to be varied until the pressure and density values derived from the assumed temperature profiles match the observed rocket and satellite data. For these reasons, temperature measurements have been attempted by several investigators who have employed "pressure" measuring devices and have obtained T/M ratio values. Here, T is measured explicitly by employing mass spectrometric techniques.

In this section, a theoretical method is presented which yields the specific determination of the temperature profile in a planetary atmosphere when the number density profiles of two gases--preferably with a large ratio in molecular weight--are known. The method, as described,

is applicable to a heterogeneous atmosphere in which the various gases are in diffusive equilibrium, obey the ideal gas law, and are not involved in chemical or physical processes which can affect the over-all composition.

In the following there will first be developed (1) a series of equations relating upper atmospheric number densities with temperatures. The application of these equations results in a temperature determination at one altitude if the temperature is known at some reference altitude. Further development yields (2) a dual gas equation in which the requirement for a known reference temperature is eliminated but the experimental requirement is correspondingly increased.

1. Single Gas Relation Between Number Density and Temperature

To derive the general equation for a number density-temperature relation, the differential equation relating the density, ρ , to the hydrostatic pressure, p , is a good starting point:

$$dp = - g \rho dz \quad (2)$$

where g denotes the acceleration of gravity and z is the geometrical altitude. For convenience, the entire calculations will be made in terms of geopotential altitude, h , which eliminates the necessity to account for changes in the acceleration of gravity with altitude. The transformation from a geometrical altitude, element dz , into a geopotential altitude, element dh , is given in Equation (3).

$$h = \frac{1}{G} \int_0^z g(z) dz \quad (3)$$

where

$$G = 9.80665 \text{ m sec}^{-2}$$

Thus,

$$G dh = g(z) dz \quad (4)$$

so that Equation (2) may be written as

$$dp = - G \rho dh \quad (4a)$$

Use of the well-known relation $P = nkT$, derived from the universal gas law, results in

$$d(nT) = - \frac{1}{k} G \rho dh \quad (5)$$

$$\left[nT \right]_b^a = - \frac{G}{k} \int_b^a \rho dh \quad (5a)$$

Substituting $\rho = nm$ and $m/k = M/R$ yields

$$n_a T_a - n_b T_b = - \frac{MG}{R} \int_b^a n dh \quad (5b)$$

which equation can be solved for T_b and/or T_a explicitly.

$$T_b = \frac{n_a}{n_b} T_a + \frac{MG}{R} \int_b^a \frac{n}{n_b} dh \quad (6)$$

$$T_a = \frac{n_b}{n_a} T_b - \frac{MG}{R} \int_b^a \frac{n}{n_a} dh \quad (7)$$

where a and b refer to upper and lower altitudes, respectively. These equations may be referred to as "single gas" equations since they are applicable to each individual number density profile. It should be remarked that the density ratios of Equations (6) and (7) can be measured directly, whereas the reference temperatures T_a and T_b in Equations (6) and (7) have to be obtained by other means. Accordingly, even if accurate density measurements for a single gas were made, a measurement of the temperature at either altitude could not be obtained without the knowledge of the corresponding reference temperature.

The following considerations are important for the application of Equations (6) and (7): If a heavy gas is considered in Equation (7), the ratio n_b/n_a and the integral $\int \frac{n}{n_a} dh$ are both very large figures. Any error of T_a becomes excessively high. Equation (7) is, therefore, not suitable for a heavy gas. On the other hand, the density ratios of Equation (6) are very small figures, and the error of T_a is reduced accordingly. If the altitude interval (a to b) is chosen sufficiently large, then the first term on the right side of Equation (6) becomes small compared to the second one and T_b becomes very insensitive to the initial choice of T_a .

For example, a density ratio 0.1 would reduce the error of T_b to 1/10 of the error of T_a . The maximum error of T_b caused by T_a would be only 10% if the T_a term is omitted completely. A reduction of density by one order of magnitude is obtained approximately every 12 km

at altitudes below 110 km. However, at higher altitudes this figure increases rapidly. For instance, one order of magnitude density drop occurs between 110 and 130 km, or 130 and 180 km, or 180 and 287 km. Therefore, this simple method of temperature determination becomes more and more impractical at altitudes above 110 km. If only direct density measurements from vacuum gauges or mass spectrometers are used, the method is limited at present to a maximum height of about 150 km. The conclusion is that the density profile of a heavy gas which covers a density range of one or more orders of magnitude can provide a good temperature value for the lowest part of the altitude region investigated, but is not suited to provide good temperature data for higher regions. In this case, use of a light gas is much more advantageous. Here, the density ratios are close to one which permits use of either Equation (6) or (7). If the T_b value has been computed from Equation (6) by use of the density profile of a heavy gas, this value T_b can be used in Equation (7) in connection with the density profile of a light gas to compute the temperature profile at higher altitudes. The error of T_a will not be much greater than the error in T_b . The value of T_a obtained in this way will be much more accurate than the original estimate used for the first application of Equation (6). A repetition of this computation process with the improved value of T_a will give improved temperature values for the entire altitude range. This iteration process can be avoided by use of the dual gas equation described in the next paragraph.

2. Dual Gas Relation Between Number Densities and Temperature

The reference temperatures can be eliminated by substitution from expressions (6) and (7) to yield the following corresponding relationships:

$$T_b = \frac{1}{\frac{n_b^*}{n_a^*} - \frac{n_b}{n_a}} \frac{G}{R} \left[M^* \int_b^a \frac{n^*}{n_a^*} dh - M \int_b^a \frac{n}{n_a} dh \right] \quad (8)$$

$$T_a = \frac{1}{\frac{n_a}{n_b} - \frac{n_a^*}{n_b^*}} \frac{G}{R} \left[M^* \int_b^a \frac{n^*}{n_b^*} dh - M \int_b^a \frac{n}{n_b} dh \right] \quad (9)$$

For clarity, the values designated by an asterisk refer to the heavy gas measurements, whereas the others refer to the light gas measurements. Since the measurements described in this report yield simultaneous measurements of the number densities of both the heavy and light gas with altitude, Equations (8) and (9) are applicable to the data. Thus, Equations (8) and (9) show that a temperature determination is now made available without the necessity of invoking or knowing some reference temperature. The application of Equations (8) and (9) will be shown in the next section which discusses a hypothetical experiment.

III. ANALYSIS OF A HYPOTHETICAL EXPERIMENT

A. GENERAL REMARKS

In this section the usefulness of the dual gas method will be described by applying it to some numerical data. However, since no experimental data are available yet, it was necessary to generate somewhat realistic data based on atmospheric parameters discussed in the Proposed 1961 Revision of U.S. Standard Atmosphere⁽¹⁾, for which it was assumed a mictopause level at 100 km with the transition region extending between 95 and 105 km. For the purpose of further discussion of this hypothetical experiment, it is assumed that primary data reduction difficulties have been either eliminated or accounted for. Typical presentation of the final data could correspond to those shown in Figures 5 and 6. Figure 5 shows the relative number density-altitude behavior of helium whereas Figure 6 shows the analogous data for argon. Further discussion of these data can more conveniently be accomplished in two parts: (1) determination of atmospheric dynamics and (2) determination and atmospheric thermodynamics.

B. ATMOSPHERIC DYNAMICS

The data in Figures 5 and 6 can be presented to detect the beginning of diffusive separation in order to define the mictopause level and the transition region. This is shown in Figure 7. The figure indicates the presence of a transition region from 95 to 105 km. Previous

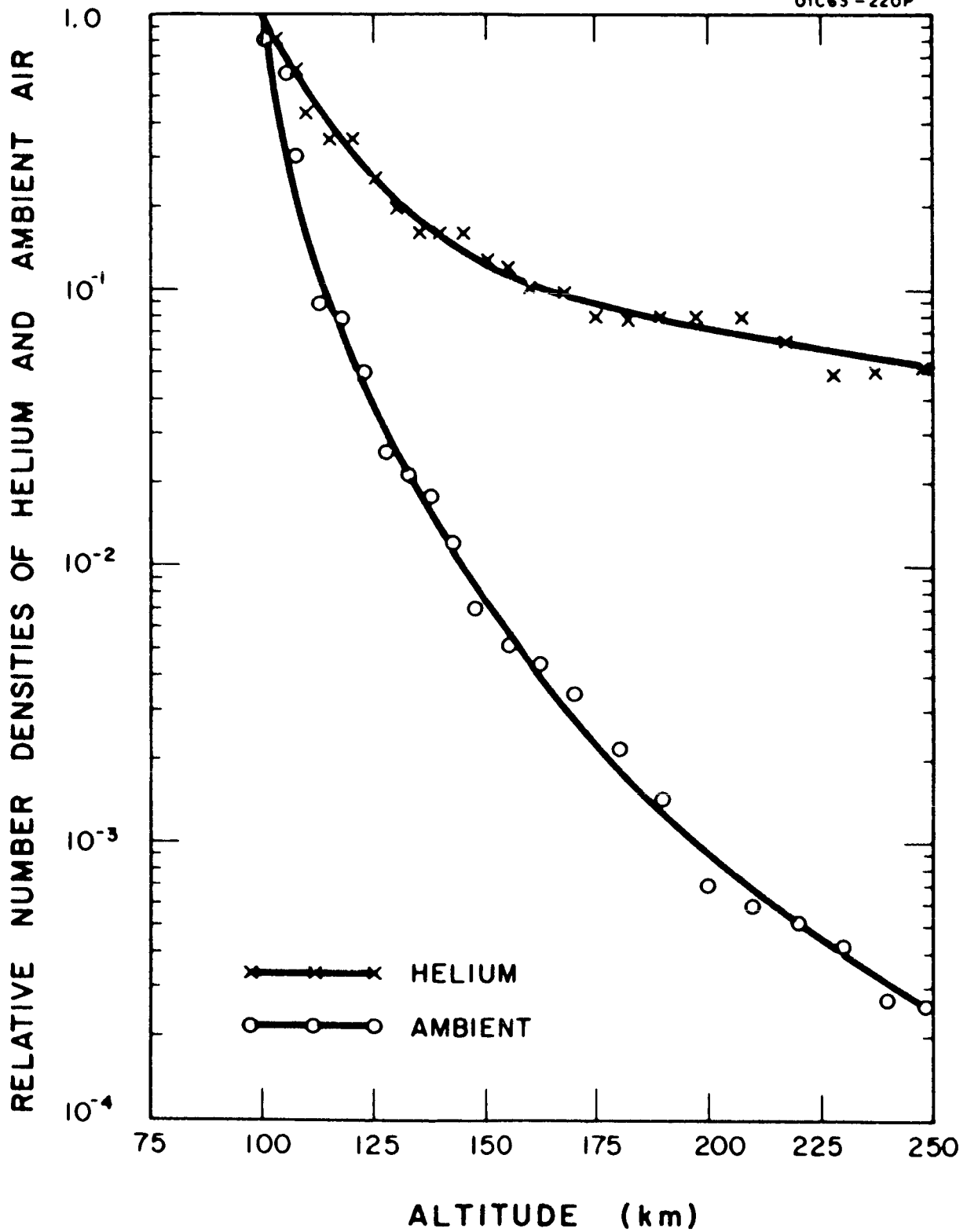


Figure 5. Experimental measurements of the relative number density of helium and ambient air between 100 and 250 km.

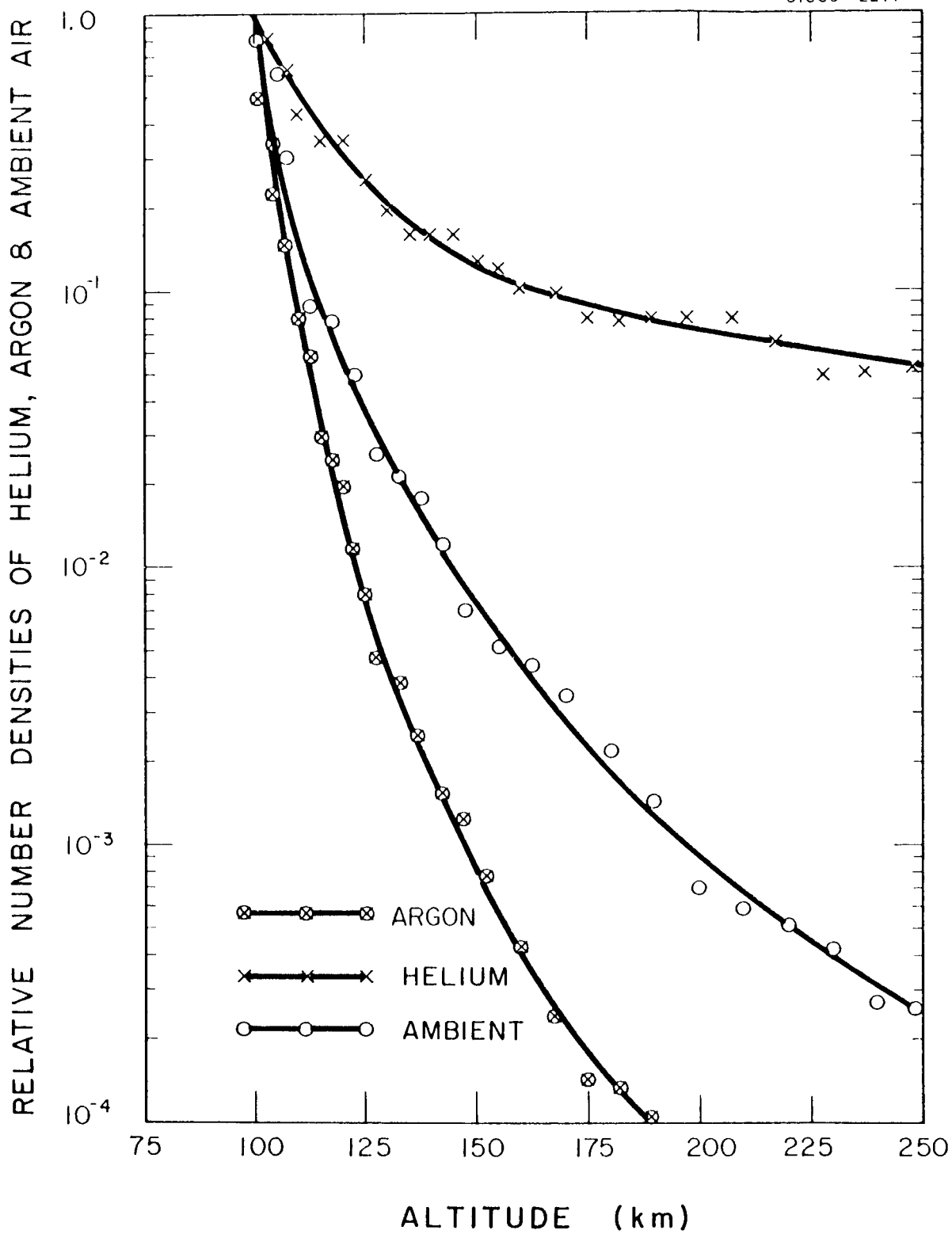


Figure 6. Experimental measurements of the relative number density of helium, argon and ambient air between 100 and 250 km.

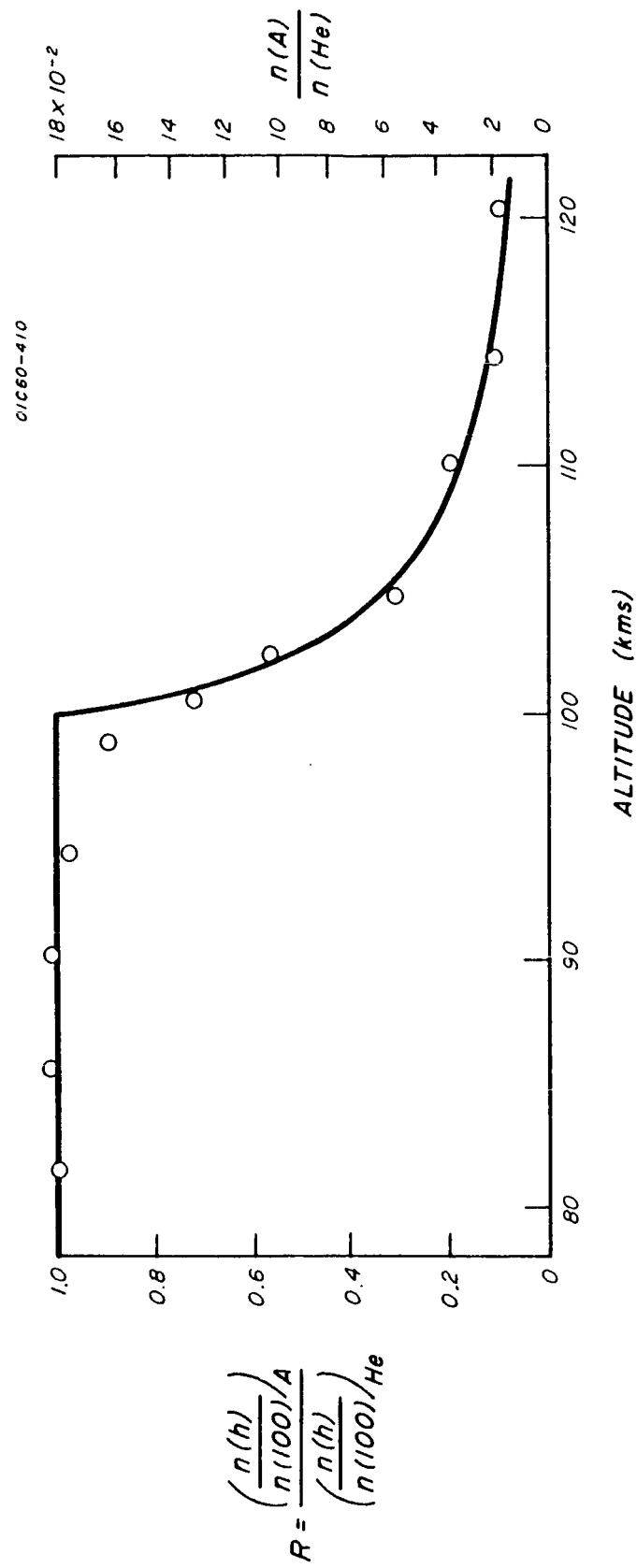


Figure 7. The diffusive separation ratio, R , as a function of altitude as derived from the data shown in Figures 5 and 6.

investigators have obtained similar information. However, the present method has the following unique advantages: (a) the mass ratio between argon and helium is 10 (as compared to only 1.5 for argon and nitrogen); (b) the noble gases do not participate in any chemical interactions; (c) the effect of ionization is negligible even at high altitudes; (d) no instrumental difficulties need be attributed to different ionization efficiencies; and finally (e) since no changes in composition of these species can occur, the atomic weights are constant throughout the entire altitude regime. Item (e) makes available an additional piece of information of considerable importance. Specifically, by determining the ratio of number density scale heights for helium and argon at various altitudes, the regions of perfect mixing, partial mixing, and complete diffusive equilibrium should be made evident. For example, for the region of perfect mixing, a ratio of 1 should prevail. This value should increase throughout the transition region until gravitational separation is complete and a value of 10 will be obtained. This behavior is shown in Figure 8.

C. ATMOSPHERIC THERMODYNAMICS

The data shown in Figures 5 and 6 can be employed for the determination of T_b and/or T_a by Equations (8) and (9) for the region in which diffusive equilibrium prevails. For example, for an Aerobee-Hi experiment the altitude region is between about 150 km (see Figure 8) and 250 km. For obtaining optimum temperature measurements, the following

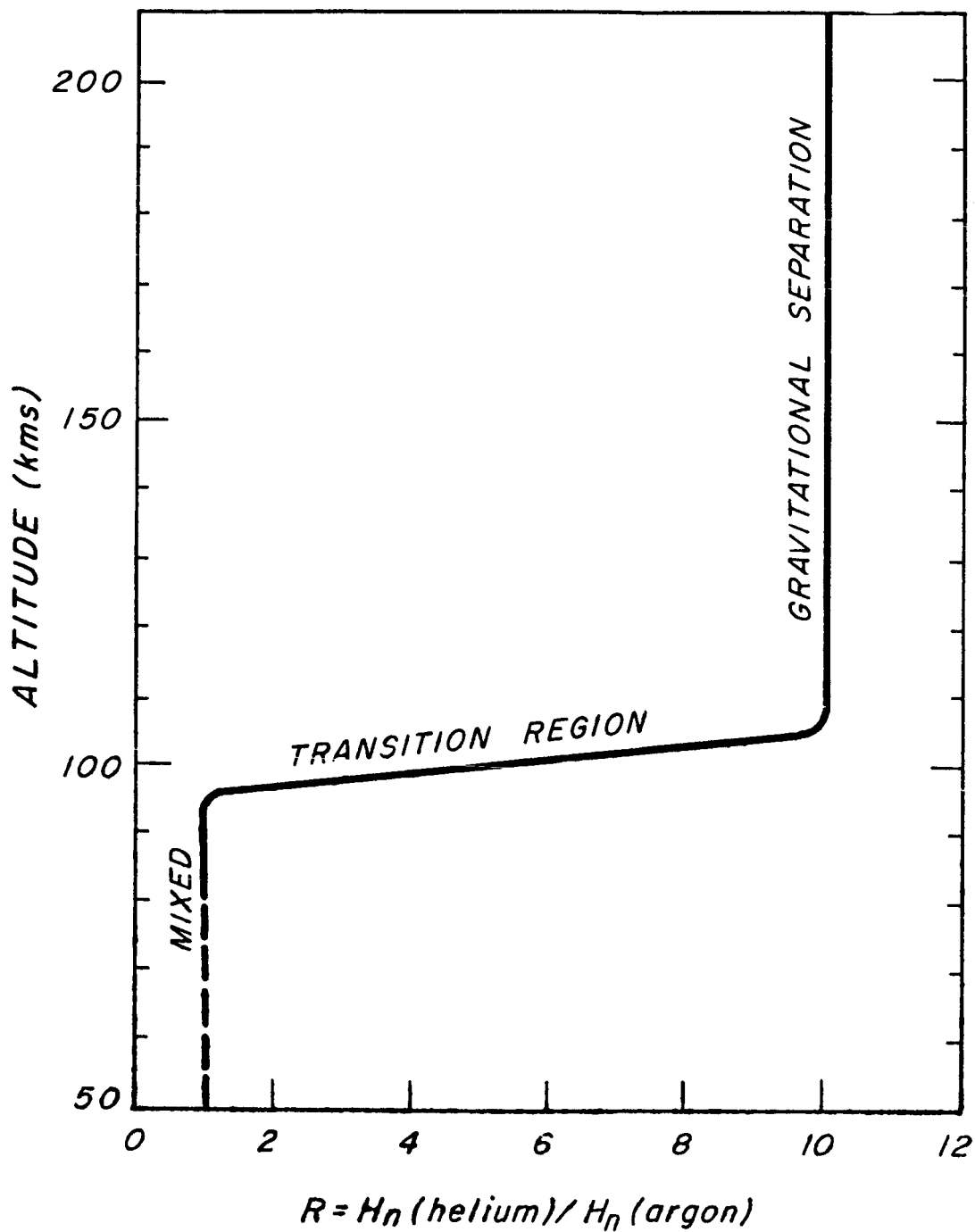


Figure 8 Number density scale heights, ratio for helium-argon at different altitudes.

sequence of computation steps can be suggested: (a) calculate T_a (at 250 km) by means of Equation (9) from the measured number density profiles of helium and argon (recall that the quantities designated by an asterisk refer to heavy gas); (b) employ this T_a -value as the reference temperature in Equation (6) to calculate an accurate value of T_b for all altitudes for which good density data have been obtained; and finally (c) the employment of this T_a -value as the reference temperature T_b in Equation (7) permits an upward extension of the temperature profile for all altitudes for which helium density data have been obtained. This procedure should result, in principle, in the determination of an accurate temperature-altitude profile. The procedure outlined is valid but does not consider the effect of instrumental error. In the real case, of course, experimental errors are involved which a more realistic approach must recognize and take account for.

It is of interest to note also that for the mixed region, a crude temperature value may be derived from these data. In the mixed region the helium peak variation with altitude roughly corresponds to the total pressure variation with altitude. Accordingly, if the mass spectrometer is capable of being employed as low as say 80 km, then the "pressure" variation between 80 and 100 km can be converted into a measure of the temperature. (The resultant temperature is not to be confused with the previously obtained T_b -value which corresponds to the lowest altitude at which diffusive equilibrium prevails.) The present value of T is applicable up to the top of the mixed region.

The helium number density profile data can also be of value in the determination of relatively small temperature perturbations in confined regions of the atmosphere. Ainsworth et al. ⁽¹¹⁾ have discussed the possible existence of temperature maxima and minima in the lowest atmosphere.

Above about 150 km the helium partial pressure is very insensitive to altitude. For example, within a 10 km range the pressure can be considered constant. Accordingly, any small perturbations due to local heating would be directly reflected at the perturbation in the helium number density. These perturbations should be more easily detected since the slope of the helium partial pressure profile is extremely small.

D. INDIRECT DETERMINATION OF THE MEAN MOLECULAR WEIGHT - ALTITUDE PROFILE

In addition to the determination of helium and argon number density explicitly, the particular mass spectrometer under consideration also measures total ion current. This corresponds to the output of an ionization gauge, and can be correlated with fair accuracy to the total number density which can be used to compute the mean molecular weight, \bar{M} . Thus,

$$\bar{M} = \frac{R}{\bar{n}} \frac{p}{k}$$

where

\bar{n} is the total number density.

From Equation (5):

$$\bar{M} = - \frac{R}{G} \left(T \frac{d \ln \bar{n}}{dh} + \frac{dT}{dh} \right) \quad (10)$$

The two-gas method yields the values for T , $\frac{dT}{dh}$ to substitute along with the experimental values of \bar{n} . Accordingly, a value for \bar{M} , the mean molecular weight, can be determined.

IV. INSTRUMENTATION

The preceding theoretical discussions are based on the assumption that it would be possible to measure the number density - altitude profiles for argon and helium. Argon measurements have been successfully performed from sounding rockets in the past⁽³⁾ and no principal difficulty is expected here. On the other hand, helium measurements, although tried, have not been performed successfully yet. The reason is the low relative concentration of helium in the homosphere. Single-stage mass spectrometers are not capable of an accurate helium determination in air at ground level since the background around the helium peak is excessively high. This background is caused by heavy particles (N_2^+ , O_2^+) which are scattered on the neutral gas molecules in the analyzer.

An experimental study was conducted as part of Contract NASw-25 to determine the feasibility of obtaining accurate helium measurements. For this purpose a special mass spectrometer was built which consisted of two analyzer stages and was equipped with an electron multiplier as an ion detector. The background was suppressed completely and the electrical noise was sufficiently low that it should be possible to detect helium at partial pressures as low as 3×10^{-13} torr. Air at 10^{-6} torr produced a large helium peak--big enough to permit an accurate measurement of the helium partial pressure. Based on these promising results, a prototype flight model has been built. The dimensions of this instrument have been reduced to permit installation in the nose cone of an Aerobee-Hi rocket.

The performance of this instrument, which is described in detail elsewhere⁽¹²⁾ and which is shown in Figure (7), was similar to the one mentioned above. It is capable of measuring the helium number density accurately as well as the total atmospheric density up to the peak height of the Aerobee-Hi rocket.

A very important consideration for the design of the experiment is the correlation of ambient density and the partial pressure in the mass spectrometer ion source. The latter one can be correlated easily to the peak heights of the mass spectrum after calibration in the laboratory. The computation of ambient partial densities from "gauge" partial pressures requires, in general, the knowledge of the ambient temperature. However, for two special experiments the knowledge of the ambient temperature is not required:

(1) If the intake tube is directed forward through the tip of the nose cone and the rocket speed is about equal to or larger than the most probable velocity of the molecules under consideration. In this case, the ambient density, ρ , is given by⁽¹⁴⁾

$$\rho = \frac{P}{V} \cdot \sqrt{\frac{M}{2\pi RT_g}} \quad (11)$$

where

P = pressure in the ion source

V = component of relative air velocity normal to the opening of the intake tube

T_g = temperature of the walls of the gauge or ion source

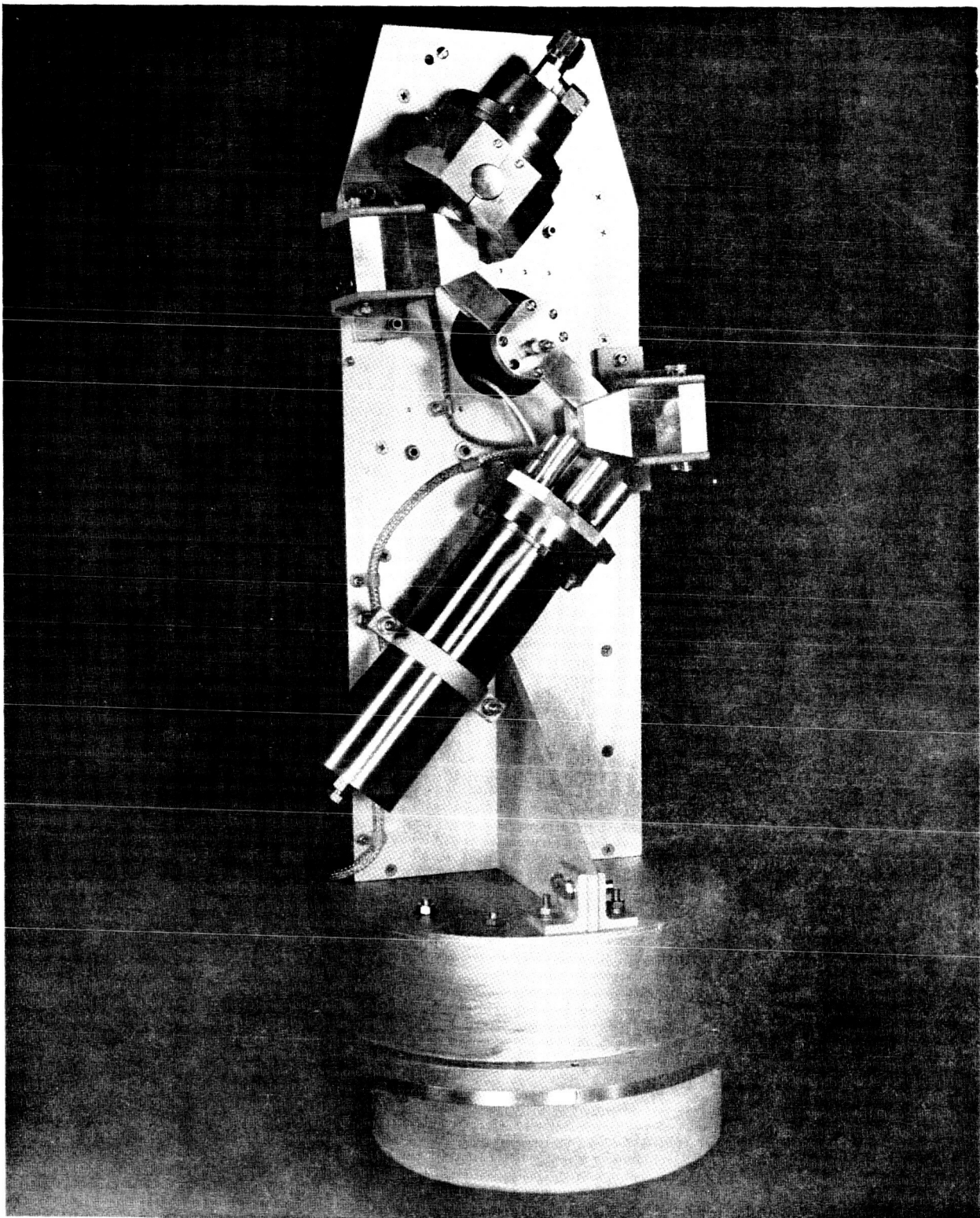


Figure 9. Photograph of the He Mass Spectrometer.

The error which is introduced by this equation due to insufficiently large rocket speeds can be greatly reduced by the method of successive approximation in connection with a more general formula. Method (1), as described above, has the following advantages: The evaluation is insensitive to the angle of attack and does not require its exact determination. The ram pressure is higher than the ambient pressure which increases the height of the upper altitude limit of the instrumentation. The disadvantages are: The height of the lower altitude limit is also increased; the method cannot be applied near the peak height of the rocket trajectory since the speed of the rocket is too low there; outgassing becomes a serious problem at higher altitudes.

(2) The second alternative is to have the intake tube extended through the cylindrical side wall of the rocket. (15) If the rocket is spinning around its axis and the axis is tilted against the direction of motion, then the intake tube will look alternatively slightly forward or backward during each spin-cycle of the rocket. This causes a pressure modulation ΔP in the gauge or mass spectrometer which can be correlated to the ambient density

$$\rho = \frac{\Delta P}{V_{\max}} \cdot \sqrt{\frac{M}{2\pi RT_g}}$$

where V_{\max} is the maximum value of the component of relative air velocity normal to the opening of the intake tube.

This method has the following advantages: (1) the background pressure, which is caused by outgassing of the rocket and by a gas cloud moving along, is eliminated which results in more reliable measurements at high altitudes; (2) the formula is exact even for very small values of V_{\max} near the peak of the rocket trajectory; (3) the instrumentation can start to operate at lower altitudes; and (4) the dynamic range which has to be covered by the instrumentation can be reduced. The disadvantages are: (1) the method is very sensitive to the angle of attack and requires its accurate measurement; (2) the motion of the rocket is difficult to control in a desired predetermined way; (3) the modulation of the signal is small--normally, only a few percent of the signal itself; and (4) this and the short time permitted for the measurement of each maximum and minimum reduces seriously the accuracy of the measurements

The decision as to which method should be used requires much more laboratory testing and, based on it, a thorough error analysis.

It has to be emphasized that both methods have been used successfully in the past for heavy constituents of the atmosphere. In the case of neutral helium and other rare gases like argon, the following advantages and simplifications occur. One does not have to worry about secondary effects on the walls of the intake tube like recombination of atoms to molecules or chemical reactions or discharge of ions, etc. In addition to this, contamination of the ambient air with helium from the rocket can be neglected if the rocket is pressurized with a gas which

does not contain any helium. It can, therefore, be expected that the results of the experiment herein proposed will be more reliable.

Although these considerations show that in principle it may be possible to obtain accurate helium number density measurements, much more work has to be done to actually fly this instrument. The over-all system has to include the telemetry equipment, the opening device, the aspect sensors, the programming circuit, calibration check points, and other auxiliary equipment.

It has not yet been decided whether argon and helium should be measured with two different instruments or with one single instrument equipped with two collectors. Each approach is possible and has its particular advantages and disadvantages. A thorough investigation is necessary to make this decision.

V. APPENDIX: SIMPLIFIED VERSION OF THE EXPERIMENT PREVIOUSLY DESCRIBED

Instead of using helium and argon density measurements, it is possible to use helium and air density measurements as long as the composition of the air does not change much. This is probably true up to altitudes of about 190 km where the mean molecular weight has dropped only about 7% according to measurements by Meadows and Townsend.⁽¹³⁾ It can be expected also that the ionization gauge sensitivity stays essentially constant up to this altitude. Therefore, the total ion current readings of the helium mass spectrometer described before can be used to compute the ambient total number density. It is expected that above about 160 km, contamination of the air due to rocket outgassing becomes more and more important. Reliable total density measurements will be obtained probably between 90 and 160 km. Within this limited altitude range, the method described in this report is still applicable if the heavy gas is air instead of argon and an average value of the mean molecular weight for the particular altitude range is used. The prototype instrument which has been developed would be adequate for such an experiment. However, for measurements at greater altitudes in the Earth's atmosphere and for measurement on other planets where the atmosphere composition is not sufficiently known, the more sophisticated experiment with argon and helium has definite advantages. Although more complicated, it is free of any assumption about the mean molecular weight and should, therefore, yield much more accurate results.

VI. SUMMARY

This report contains a description of an experimental technique for obtaining various hydrodynamic and thermodynamic properties of the upper atmosphere. This could be accomplished by employing two rocket-borne mass spectrometers capable of simultaneously measuring the number density-altitude relation of helium and ambient air in one instrument and argon and ambient air in the other. Brief reviews were given of the instrumentation and of the theoretical analysis to be employed in the present experiment. In addition, a typical data analysis has been performed on a hypothetical experiment. The analysis of the experimental data yielded information on the following: (1) the location and detection of the beginning of diffusive separation in the upper atmosphere; (2) a measure of the degree of diffusive separation in the transition region; (3) the location above which complete diffusive separation prevails; (4) an improved temperature-altitude profile from the beginning of diffusive separation up to extremely high altitudes; (5) determination of the temperature in the upper part of the mixed region of the atmosphere; (6) the possibility of detecting small perturbations of upper atmospheric temperature in local regions; and (7) a determination of the variation of mean molecular weight of the ambient air in the heterosphere. It should be noted here that in the present case, the temperature is determined explicitly (not the ratio of T/M). In addition, the variation of M with altitude is determined with fair accuracy. This now makes it possible to determine those thermodynamic properties which depend upon the explicit

knowledge of T and M. These include molecular volume, mean free path, and collision frequency.

A simplified experiment is described in the Appendix. It requires only one mass spectrometer and can provide useful data for a limited altitude range of the Earth's atmosphere.

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